



Quantum technologies with hybrid systems

Gershon Kurizki, Patrice Bertet, Yuimaru Kubo, Klaus Mølmer, David Petrosyan, Peter Rabl, Jörg Schmiedmayer

► To cite this version:

Gershon Kurizki, Patrice Bertet, Yuimaru Kubo, Klaus Mølmer, David Petrosyan, et al.. Quantum technologies with hybrid systems. Proceedings of the National Academy of Sciences of the United States of America, 2015, 112 (13), 10.1073/pnas.1419326112 . cea-01366669

HAL Id: cea-01366669

<https://hal-cea.archives-ouvertes.fr/cea-01366669>

Submitted on 15 Sep 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Quantum technologies with hybrid systems

Gershon Kurizki^{a,1}, Patrice Bertet^b, Yuimaru Kubo^b, Klaus Mølmer^c, David Petrosyan^{d,e}, Peter Rabi^f, and Jörg Schmiedmayer^f

^aDepartment of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel; ^bQuantronics Group, Service de Physique de l'Etat Condensé, Unité Mixte de Recherche 3680, Commissariat à l'Energie Atomique, 91191 Gif-sur-Yvette, France; ^cDepartment of Physics and Astronomy and ^dAarhus Institute of Advanced Studies, Aarhus University, DK-8000 Aarhus C, Denmark; ^eInstitute of Electronic Structure and Laser, Foundation for Research and Technology - Hellas, GR-71110 Heraklion, Crete, Greece; and ^fVienna Center for Quantum Science and Technology, Atominstitut, Vienna University of Technology Wien, A-1020 Vienna, Austria

Edited by Steven M. Girvin, Yale University, New Haven, CT, and approved January 28, 2015 (received for review October 23, 2014)

An extensively pursued current direction of research in physics aims at the development of practical technologies that exploit the effects of quantum mechanics. As part of this ongoing effort, devices for quantum information processing, secure communication, and high-precision sensing are being implemented with diverse systems, ranging from photons, atoms, and spins to mesoscopic superconducting and nanomechanical structures. Their physical properties make some of these systems better suited than others for specific tasks; thus, photons are well suited for transmitting quantum information, weakly interacting spins can serve as long-lived quantum memories, and superconducting elements can rapidly process information encoded in their quantum states. A central goal of the envisaged quantum technologies is to develop devices that can simultaneously perform several of these tasks, namely, reliably store, process, and transmit quantum information. Hybrid quantum systems composed of different physical components with complementary functionalities may provide precisely such multitasking capabilities. This article reviews some of the driving theoretical ideas and first experimental realizations of hybrid quantum systems and the opportunities and challenges they present and offers a glance at the near- and long-term perspectives of this fascinating and rapidly expanding field.

hybrid quantum systems | quantum technologies | quantum information

During the last several decades, quantum physics has evolved from being primarily the conceptual framework for the description of microscopic phenomena to providing inspiration for new technological applications. A range of ideas for quantum information processing (1) and secure communication (2, 3), quantum enhanced sensing (4–8), and the simulation of complex dynamics (9–14) has given rise to expectations that society may before long benefit from such quantum technologies. These developments are driven by our rapidly evolving abilities to experimentally manipulate and control quantum dynamics in diverse systems, ranging from single photons (2, 13), atoms and ions (11, 12), and individual electron and nuclear spins (15–17), to mesoscopic superconducting (14, 18) and nanomechanical devices (19, 20). As a rule, each of these systems can execute one or a few specific tasks, but no single system can be universally suitable for all envisioned applications. Thus, photons are best suited for transmitting quantum information, weakly interacting spins may serve as long-lived quantum memories, and the dynamics of electronic states of atoms or electric charges in semiconductors and superconducting elements may realize rapid processing of information encoded in their quantum states. The implementation of devices that can simultaneously perform several or all of these tasks, e.g., reliably store,

process, and transmit quantum states, calls for a new paradigm: that of hybrid quantum systems (HQSs) (15, 21–24). HQSs attain their multitasking capabilities by combining different physical components with complementary functionalities.

Many of the early ideas for HQSs emerged from the field of quantum information processing and communication (QIPC) and were, to a large extent, inspired by the development of QIPC architectures in which superconducting qubits are coupled to high-quality microwave resonators (18, 25). Superconducting qubits are very-well-controlled quantum systems (26, 27), but in contrast to atoms, they suffer from comparatively short coherence times and do not couple coherently to optical photons. A microwave resonator, such as, for example, a lumped-element LC-circuit or coplanar waveguide (CPW) resonator, can serve as an interface between superconducting qubits and also between superconducting qubits and other quantum systems with longer coherence times and optical transitions (18, 22, 23, 28). It has thus been proposed to couple superconducting qubits, via a “microwave quantum bus,” to ions (29), atoms (30–32), polar molecules (33), electrons confined above a liquid helium surface (34), and spin-doped crystals (15, 35–37). With the recent advances in the control of micro- and nanomechanical systems (19, 20), the use of a mechanical quantum bus has

also been identified as an alternative promising route for interfacing and communicating between various quantum systems (24, 38). Here one exploits the ability of functionalized resonators to respond sensitively to weak electric, magnetic, or optical signals while still being sufficiently well isolated from the environment to enable coherent transmission of quantum states.

Nearly a decade after the initial proposals, the HQS idea has developed into a rapidly growing interdisciplinary field of research. The basic working principles of HQS have by now been demonstrated in several experiments, and a growing number of theoretical and experimental research activities is presently devoted to further exploration of this approach. It is thus timely to assess the current status of the field and highlight some of its most promising short- and long-term perspectives. In what follows, this is done by reviewing the overarching goals and focusing on a few examples of HQS representing some of the most active research directions in this field. References are provided where the reader may find further information on this field.

Author contributions: G.K., P.B., Y.K., K.M., D.P., P.R., and J.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

¹To whom correspondence should be addressed. Email: gershon.kurizki@weizmann.ac.il.

General Concepts and Experimental Implementations of HQSs

A necessary prerequisite for realizing a functional HQS is the ability to communicate quantum states and properties between its different components with high fidelity. For two physical systems A and B, this requires an interaction Hamiltonian H_{AB} , which either conditions the evolution of one system on the state of the other or drives, in a correlated fashion, transitions in the two systems. In most of the examples discussed below, we will encounter interaction Hamiltonians of the form

$$H_{AB} \simeq \hbar g_{\text{eff}} (a^\dagger b + b^\dagger a), \quad [1]$$

where a (a^\dagger) and b (b^\dagger) are de-excitation (excitation) operators, which, in a generic sense, cause transitions between states within systems A and B, respectively. The product $a^\dagger b$ thus indicates a swap process in which an excitation in one system is accompanied by a de-excitation in the other. With an appropriate identification of the operators, Eq. 1 represents interacting systems such as quantum optical fields coupled by a beam splitter, atoms interacting resonantly

with a cavity field, and naturally occurring spins interacting via their magnetic moments.

If systems A and B have very different physical properties, it may be difficult to identify appropriate degrees of freedom that experience interactions of the form of Eq. 1. One obstacle may arise from the effective coupling strength g_{eff} being weak due to inadequate spatial (or impedance) matching between the systems. The couplings between microscopic systems, such as the spin-orbit and spin-spin interactions responsible for fine and hyperfine structure in atoms and molecules, are relatively strong because the electrons and nuclei are confined within Ångström distances. Alternatively, mesoscopic superconducting qubits may strongly couple to each other because of their large electric dipoles, associated with the spatial extent of the region traversed by the sustained electric currents. However, when a single atom, ion, or electron is placed near a micrometer- or millimeter-sized superconducting system, the coupling between the two is several orders of magnitude weaker. Another common challenge is rooted in the difference of the energy scales in the systems that we intend to couple. Even in the presence of a strong

interaction, the swap process described by H_{AB} will not take place if it does not conserve energy, meaning that the excitation energies of the two subsystems are very dissimilar. Much of the research in the field of HQS is devoted to overcoming these obstacles.

In Fig. 1, we illustrate various candidate components of HQSs, characterized by their typical Bohr excitation frequencies (vertical axis) and their coherence times (horizontal axis). The location of each system on the horizontal axis of the figure identifies the tasks that are best delegated to that component of a HQS: e.g., spins are useful for storage, whereas superconducting qubits may be more practical for rapid processing of quantum states. The coherence time T_2 , i.e., the time over which quantum superposition states survive, determines the minimal coupling strength required for a HQS component to function with sufficiently high fidelity: The (effective) coupling rate g_{eff} between systems A and B must be large enough to allow quantum state transfer between them within the shortest coherence time of the two, $g_{\text{eff}} T_2 \min \gg 1$.

The arrows connecting different components of HQS in Fig. 1 are labeled by approximate values of g_{eff} that can be realistically achieved with present-day technology. Some of the larger coupling strengths in Fig. 1 seem to contradict our observation concerning the weak coupling between very different physical systems. This contradiction is resolved by noting that the coupling of a mesoscopic system via light or microwave fields to ensembles rather than to single atoms or spin dopants (see below). The red and blue arrows in the figure indicate the single-system and ensemble coupling strengths, respectively. Fig. 1 also shows various examples for the coupling of systems with strongly dissimilar excitation energies (dashed lines). In such cases, the coupling mechanism involves an external source or sink, such as a (classical) laser or microwave field, which bridges the energy mismatch to make the processes described by Eq. 1 resonant when they are accompanied by absorption or stimulated emission of photons. This coupling mechanism applies to the well-known processes of laser-assisted optical Raman transitions in atoms and molecules. In optomechanics (20), parametric coupling via an applied control field is used to bridge the energy difference between mechanical vibrational modes and optical photons and to enhance the interaction strength g_{eff} .

We next present in more detail the specifics of different systems sketched in Fig. 1 and describe some of the ideas for their hybridization.

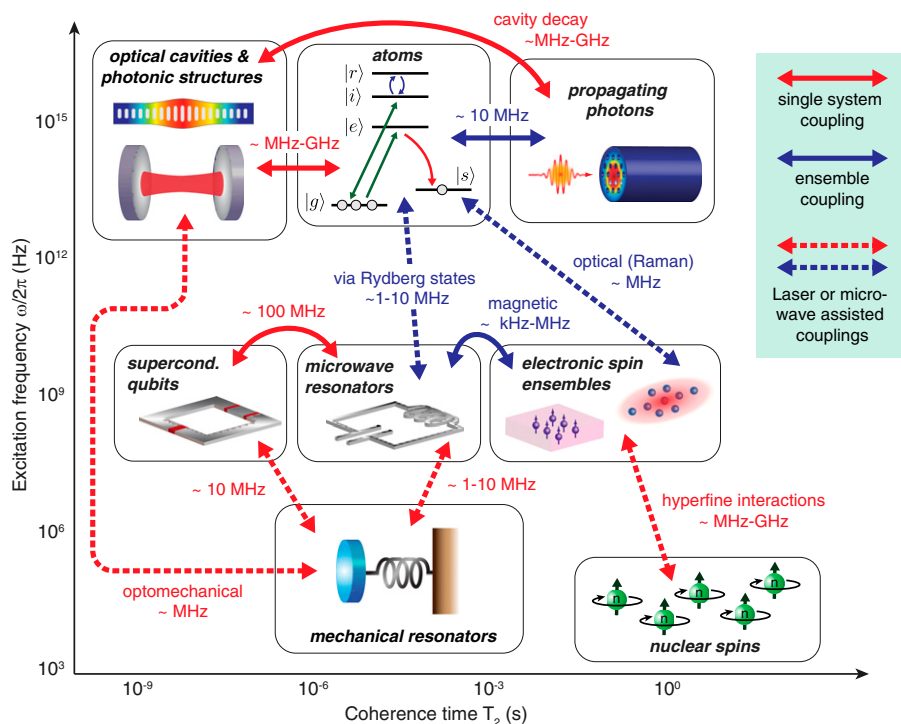


Fig. 1. HQS overview. The diagram shows a selection of physical systems that represent components of HQS with different functionalities. The individual systems are positioned in the diagram according to their characteristic excitation frequencies (vertical axis) and coherence times (horizontal axis). The arrows indicate possible coupling mechanisms and the corresponding coupling strengths g_{eff} that can be realistically achieved. The red and the blue arrows represent the coupling between single systems and the coupling to and between ensembles, respectively. Couplings represented by dashed lines are assisted by additional classical laser or microwave fields to bridge the apparent mismatch of the excitation energies. See text for more detail.

the continuum of spin transition frequencies. This approach has indeed been demonstrated to lead to a significantly reduced decay of collective excitations in such systems (56). Another potentially viable approach involves a prior optimal spectral filtering of the spin ensemble (57), which leaves an appropriate subset of the spins to serve as a high-fidelity memory. Finally, because individual spins in the inhomogeneously broadened ensemble evolve unitarily, each having its own transition frequency, the precession direction of all of the spins can be reversed by applying well-known refocusing techniques, such as Hahn echo sequences used in magnetic resonance experiments. This refocusing can enable the retrieval of the stored quantum state as a spin-echo long after the ensemble state would have lost its phase coherence due to inhomogeneous broadening (58–61).

On the other hand, inhomogeneous broadening and its effective refocusing by π pulses offer the possibility of using the spin ensemble for multimode storage. Because the photonic excitation stored in the ensemble at time t is dephased during time T_2^* , another photon can be transferred to a collective spin-excitation mode at time $t + \tau$, if $\tau > T_2^*$. By exploiting the vanishing overlap between any two such storage modes, this transfer process can be repeated several times (58–61). The number of photon pulses stored within the homogeneous lifetime T_2 ($\gg T_2^*$) of individual spins is limited by the time-bandwidth product T_2/T_2^* , allowing the storage of up to a few hundred photonic qubits in an ensemble of NV centers (60). Encouraging experimental results have already been obtained for the sequential storage of several weak microwave pulses and their retrieval tens of microseconds later (61). Multimode storage has also been demonstrated in a phosphorus-doped silicon crystal (58). In this experiment, the strong hyperfine interaction between each individual electron and its parent ion was further exploited to convert a sequence of collective electron-spin excitations into nuclear excitations, which were then stored and subsequently transferred back to the electron spins and the microwave field after seconds of storage time.

These initial results and ideas indicate the feasibility of a practical spin-ensemble quantum memory, capable of simultaneously storing the states of hundreds of superconducting qubits, for many seconds, and, potentially, for hours. Such memories would constitute a prime example of the benefits of the HQS approach.

Atomic Ensembles as Memories and Optical Interfaces. In addition to information processing and storage, quantum

states may be used for secure transmission of data. Distribution of data within larger QIPC architectures and practical quantum cryptography can only be achieved using optical photons propagating in free space or optical fibers (2, 3). The implementation of coherent interfaces between quantum memories, processing qubits, and “flying” optical qubits is thus of general importance in quantum information science.

Isolated atoms have optical (Raman) transitions with excellent properties for coherent absorption and emission, as well as storage of photons. Therefore, the coupling of ensembles of cold trapped atoms (31, 32) and molecules (33) to CPW resonators was among the initial proposals for HQSs capable of providing both long storage times and efficient optical interfaces. Compared with solid-state spin ensembles, cooling and trapping atoms in the vicinity of superconducting CPW, however, introduce severe experimental complications, and the realistic number of trapped particles of about $N = 10^5$ – 10^6 is much smaller than what is achievable with spin-doped crystals and hence the coupling to atomic spin ensembles is generally weaker (31).

To compensate for the reduced coupling, strong electric-dipole transitions between rotational states in polar molecules (33) or between highly excited Rydberg states of atoms (32, 62) can be used. In particular, the transitions in the range of tens of gigahertz between circular Rydberg states with huge dipole moments have been used (63) to strongly couple Rydberg atoms to single microwave photons in 3D resonators. Preliminary findings show that similar coupling can also be realized in on-chip CPW cavities (64, 65). Ref. 32 details a scheme where a cloud of atoms, initially prepared in the ground state $|g\rangle$, is coupled to a collective Rydberg excitation state via a two-photon process involving an optical pump field and a single photon of a CPW resonator. Overall, this scheme realizes an interaction Hamiltonian of the generic form given by Eq. 1

$$H = \hbar g \sqrt{N} (c R^+ + c^\dagger R), \quad [4]$$

where the operator $R^+ = (1/\sqrt{N}) \sum |r\rangle_n \langle g|$ creates a symmetric (collective) excitation of the Rydberg state $|r\rangle$, and $g = \Omega_{gi} \eta_{ir} / \delta$ is the effective two photon coupling rate. This rate is proportional to the Rabi frequency Ω_{gi} of the optical pump field between the ground state $|g\rangle$ and an intermediate Rydberg state $|i\rangle$ and the Rabi frequency η_{ir} of a single microwave photon interacting with the Rydberg states $|i\rangle$ and $|r\rangle$, and is inversely proportional to the detuning $\delta \gg \Omega_{gi}, \eta_{ir}$ from the intermediate

state. With a strong enough pump field Ω_{gi} and a very large dipole matrix element ($\eta_{ir} \sim n^2$), such as obtained for the transition between neighboring Rydberg states with high principal quantum number $n \cong 70$, the necessary effective coupling strength of $g_{\text{eff}} = g \sqrt{N} \gtrsim 1$ MHz can already be reached with a reasonable number of $N = 10^6$ atoms.

Once the state transfer between the microwave photon and the atoms is complete, additional optical transitions can be used to transfer the collective Rydberg excitation to a long-lived spin excitation in the ground-state hyperfine manifold and back or map it onto a propagating photon mode. In free space, stimulated Raman techniques, such as electromagnetically induced transparency (66), enable a coherent and reversible conversion of collective spin excitations into photons in well-defined spatiotemporal modes. This process requires, however, a large optical depth of the medium, $OD = \sigma \rho l > 1$, where σ is the single-atom absorption cross section, ρ is the atom density, and l is the length of the medium (67). By placing the atomic medium in an optical resonator with high finesse F , the transfer efficiency can be further increased, reaching the optimal value of $C/(1+C)$ (68). Here $C = F \times OD$ is the optical cooperativity that represents the key figure of merit for the optical interface. In view of the low atomic densities in such setups, the integration of atomic traps with on-chip photonic structures (69, 70) is a promising experimental approach toward achieving hybrid interfaces with $C \gg 1$.

Trapping and cooling of atoms in chip-based traps is a well-established technique, which is, however, technically demanding at cryogenic temperatures and close to a superconducting surface. Nevertheless, magnetic trapping and even cooling of a cloud of atoms down to quantum degeneracy [i.e., to Bose-Einstein condensation (BEC)] above a superconducting chip has been demonstrated (71, 72). New ways of using superconducting resonators and circuits directly for trapping are currently being explored (73). Other experimental approaches to the realization of atomic HQSs are being pursued (74), where atoms are optically trapped in the evanescent field of a tapered fiber (75). This proximity of the atoms to the fiber would enable high-fidelity conversion of atomic quantum states into propagating photons in the fiber while minimizing the perturbation of the superconducting circuit because of the localization of the trapping and Raman laser beams.

In parallel to these experimental efforts on atomic microwave-to-optics interfaces, other approaches using optical and microwave

transitions in spin-doped crystals are being developed (76, 77). The goal here is to achieve a maximal overlap between the spin excitations created by the respective optical and microwave modes while minimizing the absorption of optical photons on the superconductor. Using for this purpose larger 3D microwave resonators, instead of planar CPW, may be beneficial, because both the optical and microwave modes can have their maxima at the center of such resonators, away from the superconducting walls (77). The reduced magnetic or optical coupling to a single spin is compensated in this approach by the larger number of particles that can be enclosed within the microwave mode volume (78–80).

Mechanical Quantum Transducers. As an alternative to optical and microwave photons, quantum information can be converted and transmitted via quantized mechanical vibrations of opto- and nano-mechanical systems (19, 20). High-Q micro- and nano-mechanical resonators, such as tiny cantilevers or suspended membranes, respond very sensitively to applied forces, which makes them suitable for diverse applications relying on the detection of weak signals. When applied at the level of single quanta, the same principle of force sensing—for example, the conversion of a weak magnetic force into a detectable electric or optical signal (81, 82)—opens up

new possibilities for mechanically interfacing quantum systems of different types (24). The recently demonstrated cooling of mechanical vibrational modes close to the quantum ground state (83–85), and the current experimental efforts to couple mechanical resonators to superconducting circuits (83, 86, 87), atoms (88), and spins (89, 90) are important initial steps in this direction.

The basic ideas and potential applications of mechanical quantum transducers are illustrated in Fig. 3. The setup shown in Fig. 3A depicts a mechanical spin transducer, where localized electronic spin qubits are coupled to the quantized motion of a magnetized vibrating tip. In the presence of strong magnetic field gradients, the motion of the tip modulates the Zeeman splitting of the spin eigenstates below the tip and results in a spin-resonator interaction of the form (91)

$$H_{\text{int}} = \hbar \lambda (b + b^\dagger) \sigma_z. \quad [5]$$

Here, b is the annihilation operator for the mechanical oscillator mode, σ_z is the Pauli operator for the spin, and λ is the coupling strength per phonon. Unlike Eq. 1, H_{int} does not describe a resonant exchange of excitations. Instead, it represents a spin-dependent force, which evolves an initial spin superposition state into an equivalent superposition of displaced mechanical states. If the resonator is electrically charged, the

weak magnetic moments of the spins are effectively amplified via this process into large electric dipoles, enabling, for example, strong electric interactions between separated spin qubits. Similar principles underlie the realization of various other mechanical hybrid systems in which spins or superconducting qubits are mechanically coupled with each other or interfaced with photons (92), trapped ions (93, 94), or atomic systems (88, 95–97).

First experiments—still in the classical regime—have shown that micromechanical oscillators can be magnetically coupled to hyperfine states of cold atoms (88) or individual impurity spins (89, 90). For a coherent coupling of two or multiple qubits via mechanical channels, it is necessary to reach the regime of strong (mechanical) cooperativity, $C_m = \lambda^2 T_2 T_m > 1$ (91). Here T_2 is the qubit coherence time and $T_m^{-1} = k_B T / (\hbar Q)$ is the characteristic mechanical decoherence rate, where Q is the quality factor of the resonator mode, T is the support temperature, and k_B is Boltzmann's constant. Simple estimates show that for spin qubits, the condition $C_m > 1$ can be realistically achieved using state-of-the-art mechanical resonators with $Q \sim 10^5 - 10^6$ and working at $T \leq 1$ K temperatures (90, 91). For superconducting qubits, the electrostatic interaction with nano-mechanical resonators can be significantly stronger (98). Initial experiments accessing the full strong-coupling regime $\lambda > T_2^{-1}, T_m^{-1}$ have already been performed (83, 87).

Nano-mechanical systems are of particular interest for the development of a universal opto-mechanical (OM) transducer for coherently interfacing optical and microwave photons (38, 99–101) (Fig. 3 C and D). In OM systems, the frequency ω_c of an optical cavity mode is modulated by the motion of a mechanical resonator with mechanical frequency ω_m . Common examples of OM systems include Fabry–Perot cavities with a movable end mirror or with a semitransparent membrane placed inside the cavity (20). Nano-phonic systems (102, 103) and photonic bandgap structures (99, 104) also exhibit similar interactions. The OM system is described by the Hamiltonian

$$H = \hbar \omega_c c^\dagger c + \hbar \omega_m b^\dagger b + \hbar g_0 c^\dagger c (b + b^\dagger), \quad [6]$$

where c is the annihilation operator for the optical mode. The first two terms in this equation represent the unperturbed energies of the optical and mechanical modes, respectively, and the third term describes the radiation pressure coupling. The coupling constant g_0 is the optical frequency shift per

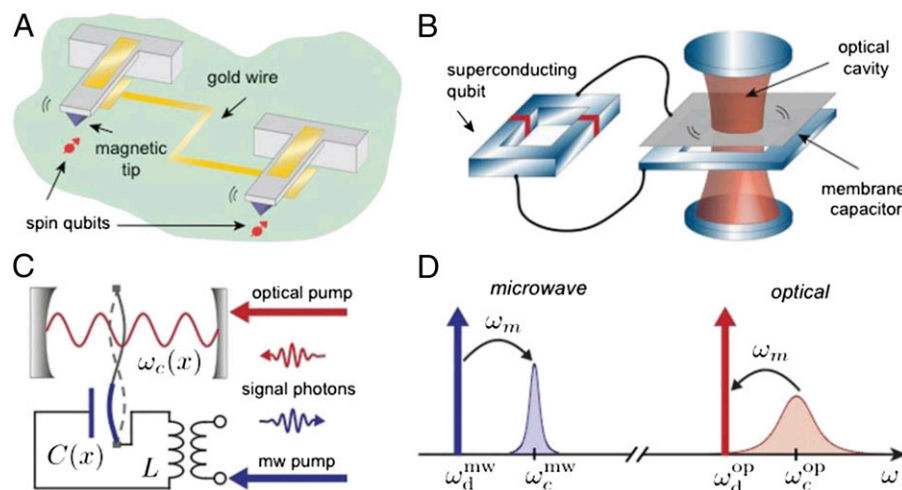


Fig. 3. Mechanical quantum transducers. (A) A magnetized mechanical resonator is coupled to a localized electronic spin qubit and converts small spin-induced displacements into electric signals. Thereby spin qubits can be “wired up” electrically or coupled to other charged quantum systems. (B) Illustration of an OM interface between a superconducting qubit and optical (flying) photons. Here the mechanical system, represented by a semitransparent membrane, simultaneously acts as a capacitor and an optical reflector. (C) Experimental setup used in ref. 108 to implement an optomechanical microwave-to-optics interface via simultaneous coupling of a partially metallized membrane to an optical cavity and an LC circuit. (D) A signal photon of frequency $\sim \omega_c^{\text{op}}$ enters the optical cavity and is down-converted via the driven, parametric OM interaction into a phonon of frequency ω_m . Then, via an equivalent process, this mechanical excitation is up-converted again into a microwave photon of frequency $\sim \omega_c^{\text{mw}}$ in the LC circuit. Via this mechanism and its reverse, quantum information encoded in microwave excitations of a superconducting qubit or LC resonator can be coherently transferred into optical signals for long-distance quantum communication.

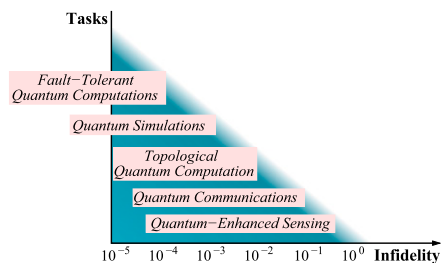


Fig. 4. Potential applications that can be performed by a HQS with achievable infidelity 1- F .

vibrational quantum, which is typically very small. However, the OM interaction can be parametrically amplified by driving the cavity with a strong laser of frequency ω_d . In this case, the total field inside the cavity is $c = [\alpha(t) + \delta c] \exp(-i\omega_d t)$, where δc represents the quantum fluctuations around a large classical field amplitude $\alpha(t)$. By choosing the resonance condition $\omega_c = \omega_d + \omega_m$, the dominant OM coupling term then becomes analogous to a beam-splitter interaction (20)

$$H_{\text{OM}} \simeq \hbar G(t)(\delta c^\dagger b + b^\dagger \delta c), \quad [7]$$

where, similar to an anti-Stokes scattering process, low-frequency mechanical excitations are up-converted by the driving field into optical signal photons and vice versa. The effective coupling $G(t) = \alpha(t)g_0$ is then enhanced and controlled by the external driving field.

In the microwave domain, an analogous coupling arises when mechanical oscillations modulate the capacitance of a superconducting CPW resonator or LC circuit (84, 105). Here too, the coupling is amplified and controlled by a strong microwave driving field that bridges the frequency difference between the circuit and mechanical resonances. It is important that due to the underlying parametric interaction, the effective photon-phonon interface in Eq. 5 does not rely on the absolute frequency of the optical or microwave mode, which in both cases is compensated by the frequency of the external driving field (Fig. 3D). Therefore, by using a single mechanical membrane as both a mirror and a capacitor, an effective optics-to-microwave interface is achieved, whereby microwave photons are converted to phonons and successively to (flying) optical photons.

Various designs for the experimental implementation of coherent microwave-to-optics transducers are currently being explored. An efficient OM conversion between optical and microwave signals has already been demonstrated in both room temperature (106, 107) and cryogenic (108) environments. Despite many obstacles that

currently still hinder a fully coherent operation of such experiments at a single-photon level, the prospects for OM quantum interfaces between solid-state, atomic, and optical systems are very promising.

Outlook: Quo Vadis, Quantum Hybridium?

Hybrid quantum systems are still a long way from implementing general quantum information processing and communication tasks with the fidelities needed for practical applications. The integration of very different physical components presents technological and scientific challenges that are absent when controlling each component individually. However, the experimental realizations of HQSs described above show that these obstacles may be overcome. Protocols with controlled time-dependent couplings are currently being investigated to optimize quantum state transfer speed and fidelity. The shape of the coupling fields can be tailored to the temporal response of the noisy (decohering) environments (109), and quantum measurements and feedback may also be applied (110), in an effort to reduce or eliminate the effect of dissipation and decoherence at HQS interfaces. There is little doubt that continued progress along these directions will enable hybrid, multitasking quantum technologies of increasing sophistication.

To provide an overview of tasks for which HQSs may be used in the near- and more-distant future, we indicate in Fig. 4 the infidelities tolerated by various potential technological applications of quantum effects. Obviously, the ultimate goal of realizing a large-scale quantum computer including algorithmic quantum error correction is beyond current capabilities. At the other, more modest, end of the scale are communication and sensing, which may function, albeit at a lower rate, even if the coupling process has a low fidelity or is heralded with low success probability. Here, HQSs are expected to have a great impact rather soon. For example, the unprecedented level of control and low-noise amplification at microwave frequencies achieved in superconducting circuits has already been used to detect an electron-spin resonance at the level of few excitations (111). Similarly, OM transducers are being explored for low-noise optical detection of weak radio frequency signals (107). More generally, the anticipated ability of HQSs to transfer highly nonclassical (entangled) states between

different physical platforms may extend quantum-enhanced sensing schemes to systems where such a high level of quantum control is a priori not available. The mapping of squeezed microwave or optical fields onto spin ensembles for magnetometry and the preparation of nanomechanical sensors in highly sensitive quantum superposition states are possible applications along these lines.

Turning from practical applications to more fundamentally oriented research, the scaling-up of HQSs may offer new possibilities to simulate and study complex phenomena in quantum many-body systems. Especially, the combination of different systems with optimized coherent and tailored (engineered) dissipative properties may be used to investigate issues related to non-equilibrium phase transitions in open quantum many-body systems (10, 112–114). Such systems are currently difficult to realize in the laboratory, but analyses of dissipative Dicke-type lattice models with HQS arrays of spin ensembles and superconducting circuits (115–118) show the potential for achieving scalable systems with sufficiently large interaction strengths.

Overall, the HQS approach concurs with the long-term vision of a “quantum information era,” in which quantum information is processed, stored, and transmitted in a modular and platform-versatile manner. The fascinating prospects of this research will keep scientists occupied for some time and are likely to stimulate many ideas and motivate experts from research and engineering areas not even mentioned in this review to confront the challenges of HQSs.

ACKNOWLEDGMENTS. We would like to thank the many colleagues and collaborators for their contributions to the field of hybrid quantum systems and to our own earlier work. This article was initiated upon successful completion of the European Commission project MIDAS (Macroscopic Interference Devices for Atoms and Solids). We acknowledge support from ISF, United States–Israel Binational Science Foundation and Alternative Energy Research Initiative (G.K.), the Villum Foundation (K.M.), the Humboldt Foundation (D.P.), European Projects SIQS (P.R. and J.S.) and SCALEQIT (Scalable Quantum Information with Transmons) (P.B., Y.K.), the Austrian Science Fund through SFB FOQUS (P.R., J.S.), the START Grant Y 591-N16 (P.R.), the Agence Nationale de la Recherche through the European Coordinated Research on Long-term Challenges in Information and Communication Sciences & Technologies ERA-Net (CHIST-ERA) program QINVC (Quantum Information with NV Centers) (P.B., Y.K.), and JSPS (Japan Society for the Promotion of Science) (Y.K.).

1 Nielsen M, Chuang I (2000) *Quantum Computation and Quantum Information* (Cambridge Univ, Cambridge, UK).

2 Gisin N, Ribordy G, Tittel W, Zbinden H (2002) Quantum cryptography. *Rev Mod Phys* 74(1):145–196.

3 Sergienko AV, ed (2006) *Quantum Communications and Cryptography* (Taylor & Francis, Boca Raton, FL).

4 Giovannetti V, Lloyd S, Maccone L (2011) Advances in quantum metrology. *Nat Photonics* 5(4):222–229.

- 5 Wolfgramm F, Vitelli C, Beduini FA, Godbout N, Mitchell MW (2013) Entanglement-enhanced probing of a delicate material system. *Nat Photonics* 7(1):28–32.
- 6 Schmidt PO, et al. (2005) Spectroscopy using quantum logic. *Science* 309(5735):749–752.
- 7 Hempel C, et al. (2013) Entanglement-enhanced detection of single-photon scattering events. *Nat Photonics* 7(8):630–633.
- 8 Ockeloen CF, Schmied R, Riedel MF, Treutlein P (2013) Quantum metrology with a scanning probe atom interferometer. *Phys Rev Lett* 111(14):143001.
- 9 Buluta I, Nori F (2009) Quantum simulators. *Science* 326(5949):108–111.
- 10 Cirac JJ, Zoller P (2012) Goals and opportunities in quantum simulation. *Nat Phys* 8(4):264–266.
- 11 Bloch I, Dalibard J, Nascimbène S (2012) Quantum simulations with ultracold quantum gases. *Nat Phys* 8(4):267–276.
- 12 Blatt R, Roos CF (2012) Quantum simulations with trapped ions. *Nat Phys* 8(4):277–284.
- 13 Aspuru-Guzik A, Walther P (2012) Photonic quantum simulators. *Nat Phys* 8(4):285–291.
- 14 Houck AA, Türeci HE, Koch J (2012) On-chip quantum simulation with superconducting circuits. *Nat Phys* 8(4):292–299.
- 15 Morton JLL, Lovett BW (2011) Hybrid solid state qubits: The powerful role of electron spins. *Annu. Rev. of Condens. Matter Phys* 2:189–212.
- 16 Maurer PC, et al. (2012) Room-temperature quantum bit memory exceeding one second. *Science* 336(6086):1283–1286.
- 17 Pla JJ, et al. (2013) High-fidelity readout and control of a nuclear spin qubit in silicon. *Nature* 496(7445):334–338.
- 18 Schoelkopf RJ, Girvin SM (2008) Wiring up quantum systems. *Nature* 451(7179):664–669.
- 19 Poot M, van der Zant H (2012) Mechanical systems in the quantum regime. *Phys Rep* 511(5):273–336.
- 20 Aspelmeier M, Kippenberg TJ, Marquardt F (2014) Cavity optomechanics. *Rev Mod Phys* 86(4):1391–1452.
- 21 Wallquist M, Hammerer K, Rabl P, Lukin M, Zoller P (2009) Hybrid quantum devices and quantum engineering. *Phys Scr T* 137:014001.
- 22 Xiang ZL, Ashhab S, You JQ, Nori F (2013) Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems. *Rev Mod Phys* 85(2):623–654.
- 23 Daniilidis N, Haefliger H (2013) Quantum interfaces between atomic and solid-state systems. *Annu. Rev. Condens. Matter Phys.* 4:83–112.
- 24 Treutlein P, Genes C, Hammerer K, Poggio M, Rabl P (2014) Hybrid mechanical systems. *Cavity Optomechanics*, eds Marquardt F, Aspelmeier M, Kippenberg T (Springer, Berlin).
- 25 Blais A, Huang R-S, Wallraff A, Girvin SM, Schoelkopf RJ (2004) Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation. *PRA* 69(6):062320.
- 26 Devoret MH, Schoelkopf RJ (2013) Superconducting circuits for quantum information: An outlook. *Science* 339(6124):1169–1174.
- 27 You JQ, Nori F (2011) Atomic physics and quantum optics using superconducting circuits. *Nature* 474(7353):589–597.
- 28 Bensky G, et al. (2011) Controlling quantum information processing in hybrid systems on chips. *Quant Info Proc* 10(6):1037–1060.
- 29 Tian L, Rabl P, Blatt R, Zoller P (2004) Interfacing quantum-optical and solid-state qubits. *Phys Rev Lett* 92(24):247902.
- 30 Sørensen AS, van der Wal CH, Childress LI, Lukin MD (2004) Capacitive coupling of atomic systems to mesoscopic conductors. *Phys Rev Lett* 92(6):063601.
- 31 Verdú J, et al. (2009) Strong magnetic coupling of an ultracold gas to a superconducting waveguide cavity. *Phys Rev Lett* 103(4):043603.
- 32 Petrosyan D, et al. (2009) Reversible state transfer between superconducting qubits and atomic ensembles. *Phys Rev A* 79(4):040304.
- 33 Rabl P, et al. (2006) Hybrid quantum processors: Molecular ensembles as quantum memory for solid state circuits. *Phys Rev Lett* 97(3):033003.
- 34 Schuster DI, Fragner A, Dykman MI, Lyon SA, Schoelkopf RJ (2010) Proposal for manipulating and detecting spin and orbital States of trapped electrons on helium using cavity quantum electrodynamics. *Phys Rev Lett* 105(4):040503.
- 35 Imamoglu A (2009) Cavity QED based on collective magnetic dipole coupling: Spin ensembles as hybrid two-level systems. *Phys Rev Lett* 102(8):083602.
- 36 Wesenberg JH, et al. (2009) Quantum computing with an electron spin ensemble. *Phys Rev Lett* 103(7):070502.
- 37 Marcos D, et al. (2010) Coupling nitrogen-vacancy centers in diamond to superconducting flux qubits. *Phys Rev Lett* 105(21):210501.
- 38 Tian L (2015) Optoelectromechanical transducer: Reversible conversion between microwave and optical photons. *Ann Phys* 527:1–14.
- 39 Paik H, et al. (2011) Observation of high coherence in Josephson junction qubits measured in a three-dimensional circuit QED architecture. *Phys Rev Lett* 107(24):240501.
- 40 Barends R, et al. (2013) Coherent Josephson qubit suitable for scalable quantum integrated circuits. *Phys Rev Lett* 111(8):080502.
- 41 Bar-Gill N, Pham LM, Jarmola A, Budker D, Walsworth RL (2013) Solid-state electronic spin coherence time approaching one second. *Nat Commun* 4:1743.
- 42 Saeedi K, et al. (2013) Room-temperature quantum bit storage exceeding 39 minutes using ionized donors in silicon-28. *Science* 342(6160):830–833.
- 43 Schuster DI, et al. (2010) High-cooperativity coupling of electron-spin ensembles to superconducting cavities. *Phys Rev Lett* 105(14):140501.
- 44 Ranjan V, et al. (2013) Probing dynamics of an electron-spin ensemble via a superconducting resonator. *Phys Rev Lett* 110(6):067004.
- 45 Kubo Y, et al. (2010) Strong coupling of a spin ensemble to a superconducting resonator. *Phys Rev Lett* 105(14):140502.
- 46 Amsüss R, et al. (2011) Cavity QED with magnetically coupled collective spin states. *Phys Rev Lett* 107(6):060502.
- 47 Probst S, et al. (2013) Anisotropic rare-earth spin ensemble strongly coupled to a superconducting resonator. *Phys Rev Lett* 110(15):157001.
- 48 Huebl H, et al. (2013) High cooperativity in coupled microwave resonator ferromagnetic insulator hybrids. *Phys Rev Lett* 111(12):127003.
- 49 Tabuchi Y, et al. (2014) Hybridizing ferromagnetic magnons and microwave photons in the quantum limit. *Phys Rev Lett* 113(8):083603.
- 50 Zhang X, Zou C-L, Jiang L, Tang HX (2014) Strongly coupled magnons and cavity microwave photons. *Phys Rev Lett* 113(15):156401.
- 51 Goryachev M, et al. (2014) High-cooperativity cavity QED with magnons at microwave frequencies. *Phys Rev Applied* 2(5):054002.
- 52 Zhu X, et al. (2011) Coherent coupling of a superconducting flux qubit to an electron spin ensemble in diamond. *Nature* 478(7368):221–224.
- 53 Kubo Y, et al. (2011) Hybrid quantum circuit with a superconducting qubit coupled to a spin ensemble. *Phys Rev Lett* 107(22):220501.
- 54 Saito S, et al. (2013) Towards realizing a quantum memory for a superconducting qubit: Storage and retrieval of quantum states. *Phys Rev Lett* 111(10):107008.
- 55 Tabuchi Y, et al. (2014) Coherent coupling between ferromagnetic magnon and superconducting qubit. arXiv:1410.3781.
- 56 Putz S, et al. (2014) Protecting a spin ensemble against decoherence in the strong-coupling regime of cavity QED. *Nat Phys* 10(10):720–724.
- 57 Bensky G, Petrosyan D, Majer J, Schmiedmayer J, Kurizki G (2012) Optimizing inhomogeneous spin ensembles for quantum memory. *Phys Rev A* 86(1):012310.
- 58 Wu H, et al. (2010) Storage of multiple coherent microwave excitations in an electron spin ensemble. *Phys Rev Lett* 105(14):140503.
- 59 Afzelius M, Sangouard N, Johansson G, Staudt MU, Wilson CM (2013) Proposal for a coherent quantum memory for propagating microwave photons. *New J Phys* 15(6):065008.
- 60 Julsgaard B, Grezes C, Bertet P, Mølmer K (2013) Quantum memory for microwave photons in an inhomogeneously broadened spin ensemble. *Phys Rev Lett* 110(25):250503.
- 61 Grezes C, et al. (2014) Multimode storage and retrieval of microwave fields in a spin ensemble. *Phys Rev X* 4(2):021049.
- 62 Petrosyan D, Fleischhauer M (2008) Quantum information processing with single photons and atomic ensembles in microwave coplanar waveguide resonators. *Phys Rev Lett* 100(17):170501.
- 63 Raimond J-M, Brune M, Haroche S (2001) Manipulating quantum entanglement with atoms and photons in a cavity. *Rev Mod Phys* 73(3):565–582.
- 64 Hogan SD, et al. (2012) Driving Rydberg-Rydberg transitions from a coplanar microwave waveguide. *Phys Rev Lett* 108(6):063004.
- 65 Hermann-Avilgiano C, et al. (2014) Long coherence times for Rydberg qubits on a superconducting atom chip. *Phys Rev A* 90(4):040502.
- 66 Fleischhauer M, Imamoglu A, Marangos JP (2005) Electromagnetically induced transparency: Optics in coherent media. *Rev Mod Phys* 77(2):633–674.
- 67 Gorshkov AV, André A, Fleischhauer M, Sørensen AS, Lukin MD (2007) Universal approach to optimal photon storage in atomic media. *Phys Rev Lett* 98(12):123601.
- 68 Gorshkov AV, André A, Lukin MD, Sørensen AS (2007) Photon storage in Λ -type optically dense atomic media. I. Cavity model. *Phys Rev A* 76(3):033804.
- 69 Hung C-L, Meenehan SM, Chang DE, Painter O, Kimble HJ (2013) Trapped atoms in one-dimensional photonic crystals. *New J Phys* 15(8):083026.
- 70 Tiecke TG, et al. (2014) Nanophotonic quantum phase switch with a single atom. *Nature* 508(7495):241–244.
- 71 Nirrengarten T, et al. (2006) Realization of a superconducting atom chip. *Phys Rev Lett* 97(20):200405.
- 72 Bernon S, et al. (2013) Manipulation and coherence of ultra-cold atoms on a superconducting atom chip. *Nat Commun* 4:2380.
- 73 Bothner D, et al. (2013) Inductively coupled superconducting half wavelength resonators as persistent current traps for ultracold atoms. *New J Phys* 15(9):093024.
- 74 Hafezi M, et al. (2012) Atomic interface between microwave and optical photons. *Phys Rev A* 85(2):020302.
- 75 Vetsch E, et al. (2010) Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber. *Phys Rev Lett* 104(20):203603.
- 76 O'Brien C, Laik N, Blum S, Morigi G, Fleischhauer M (2014) Interfacing superconducting qubits and telecom photons via a rare-earth-doped crystal. *Phys Rev Lett* 113(6):063603.
- 77 Williamson LA, Chen YH, Longdell JJ (2014) Magneto-optic modulator with unit quantum efficiency. *Phys Rev Lett* 113(20):203601.
- 78 Chiorescu I, Groll N, Bertaina S, Mori T, Miyashita S (2010) Magnetic strong coupling in a spin-photon system and transition to classical regime. *Phys Rev B* 82(2):024413.
- 79 Abe E, Wu H, Ardaev A, Morton JLL (2011) Electron spin ensemble strongly coupled to a three-dimensional microwave cavity. *Appl Phys Lett* 98(25):251108.
- 80 Probst S, et al. (2014) Three-dimensional cavity quantum electrodynamics with a rare-earth spin ensemble. *Phys Rev B* 90(10):100404.
- 81 Rugar D, Budakian R, Mamin HJ, Chui BW (2004) Single spin detection by magnetic resonance force microscopy. *Nature* 430(6997):329–332.
- 82 Poggio M, Degn CL (2010) Force-detected nuclear magnetic resonance: Recent advances and future challenges. *Nanotechnology* 21(34):342001.
- 83 O'Connell AD, et al. (2010) Quantum ground state and single-phonon control of a mechanical resonator. *Nature* 464(7289):697–703.
- 84 Teufel JD, et al. (2011) Sideband cooling of micromechanical motion to the quantum ground state. *Nature* 475(7356):359–363.
- 85 Chan J, et al. (2011) Laser cooling of a nanomechanical oscillator into its quantum ground state. *Nature* 478(7367):89–92.
- 86 LaHaye MD, Suh J, Echterbach PM, Schwab KC, Roukes ML (2009) Nanomechanical measurements of a superconducting qubit. *Nature* 459(7249):960–964.
- 87 Pirkkalainen J-M, et al. (2013) Hybrid circuit cavity quantum electrodynamics with a micromechanical resonator. *Nature* 494(7436):211–215.
- 88 Hunger D, et al. (2010) Resonant coupling of a Bose-Einstein condensate to a micromechanical oscillator. *Phys Rev Lett* 104(14):143002.
- 89 Arcizet O, et al. (2011) A single nitrogen-vacancy defect coupled to a nanomechanical oscillator. *Nat Phys* 7(11):879–883.
- 90 Kolkowitz S, et al. (2012) Coherent sensing of a mechanical resonator with a single-spin qubit. *Science* 335(6076):1603–1606.
- 91 Rabl P, et al. (2010) A quantum spin transducer based on nano electro-mechanical resonator arrays. *Nat Phys* 6(8):602–608.
- 92 Stannigel K, Rabl P, Sørensen AS, Zoller P, Lukin MD (2010) Optomechanical transducers for long-distance quantum communication. *Phys Rev Lett* 105(22):220501.
- 93 Tian L, Zoller P (2004) Coupled ion-nanomechanical systems. *Phys Rev Lett* 93(26 Pt 1):266403.
- 94 Hensinger WK, et al. (2005) Ion trap transducers for quantum electromechanical oscillators. *Phys Rev A* 72(4):041405.
- 95 Hammerer K, et al. (2009) Strong coupling of a mechanical oscillator and a single atom. *Phys Rev Lett* 103(6):063005.
- 96 Gao M, Liu Y, Wang X-B (2011) Coupling Rydberg atoms to superconducting qubits via nanomechanical resonator. *Phys Rev A* 83(2):022309.
- 97 Bariani F, et al. (2014) Single-atom quantum control of macroscopic mechanical oscillators. *Phys Rev A* 89(1):011801.
- 98 Armour AD, Blencowe MP, Schwab KC (2002) Quantum Dynamics of a Cooper-Pair Box Coupled to a Micromechanical Resonator. *Phys Rev Lett* 88:148301.
- 99 Safavi-Naeini AH, Painter O (2011) Proposal for an optomechanical traveling wave phonon-photon translator. *New J Phys* 13(1):013017.
- 100 Regal CA, Lehnert KW (2011) From cavity electromechanics to cavity optomechanics. *J Phys Conf Ser* 264(1):012025.
- 101 Taylor JM, Sørensen AS, Marcus CM, Polzik ES (2011) Laser cooling and optical detection of excitations in a LC electrical circuit. *Phys Rev Lett* 107(27):273601.
- 102 Ding L, et al. (2011) Wavelength-sized GaAs optomechanical resonators with gigahertz frequency. *Appl Phys Lett* 98(11):113108.
- 103 Verhagen E, Deléglise S, Weis S, Schliesser A, Kippenberg TJ (2012) Quantum-coherent coupling of a mechanical oscillator to an optical cavity mode. *Nature* 482(7383):63–67.

- 104** Sun X, Zhang X, Poot M, Xiong C, Tang HX (2012) A superhigh-frequency optoelectromechanical system based on a slotted photonic crystal cavity. *Appl Phys Lett* 101(22):221116.
- 105** Teufel JD, et al. (2011) Circuit cavity electromechanics in the strong-coupling regime. *Nature* 471(7337):204–208.
- 106** Bochmann J, Vainsencher A, Awschalom DD, Cleland AN (2013) Nanomechanical coupling between microwave and optical photons. *Nat Phys* 9(11):712–716.
- 107** Bagci T, et al. (2014) Optical detection of radio waves through a nanomechanical transducer. *Nature* 507(7490):81–85.
- 108** Andrews RW, et al. (2014) Bidirectional and efficient conversion between microwave and optical light. *Nat Phys* 10(4):321–326.
- 109** Zwick A, Álvarez GA, Bensky G, Kurizki G (2014) Optimized dynamical control of state transfer through noisy spin chains. *New J Phys* 16(6):065021.
- 110** Wiseman HM, Milburn GJ (2010) *Quantum Measurement and Control* (Cambridge Univ Press, Cambridge, UK).
- 111** Kubo Y, et al. (2013) Electron spin resonance detected by a superconducting qubit. *Phys Rev B* 86(6):064514.
- 112** Diehl S, et al. (2008) Quantum states and phases in driven open quantum systems with cold atoms. *Nat Phys* 4(9):878–883.
- 113** Verstraete F, Wolf MM, Cirac JJ (2009) Quantum computation and quantum-state engineering driven by dissipation. *Nat Phys* 5(7):633–636.
- 114** Müller M, Diehl S, Pupillo G, Zoller P (2012) Engineered open systems and quantum simulations with atoms and ions. *Adv At Mol Opt Phys* 61:1–80.
- 115** Yang WL, et al. (2012) Quantum simulation of an artificial Abelian gauge field using nitrogen-vacancy-center ensembles coupled to superconducting resonators. *Phys Rev A* 86(1):012307.
- 116** Hümmer T, Reuther GM, Hänggi P, Zueco D (2012) Nonequilibrium phases in hybrid arrays with flux qubits and nitrogen-vacancy centers. *Phys Rev A* 85(5):052320.
- 117** Qiu Y, Xiong W, Tian L, You JQ (2014) Coupling spin ensembles via superconducting flux qubits. *Phys Rev A* 89(4):042321.
- 118** Zou LJ, et al. (2014) Implementation of the Dicke lattice model in hybrid quantum system arrays. *Phys Rev Lett* 113(2):023603.